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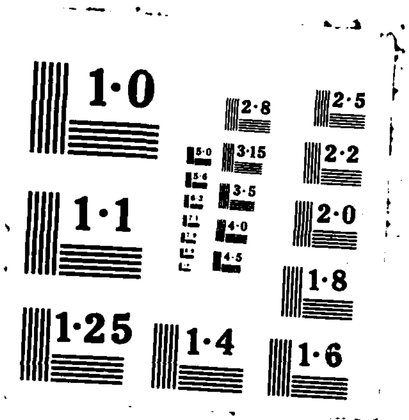
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October 1986

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Abstract

The substorm which occurs on 22 March 1979 offers a particularly clear example of isolated activity. At the onset at 1054 UT and subsequently, both ISEE spacecraft are located close to both the midplane of the tail and local midnight. Plasma sheet thinning occurs prior to onset, and at onset strong plasma flows are observed at both ISEE spacecraft. The net flow direction is initially tailward, although there are persistent slow flows directed earthward. Some time later there are strong flows earthward, coincident with plasma sheet recovery. In this study we focus on the three-dimensional velocity distributions measured on ISEE 1, in particular the low-energy plasma population which coexists with the energetic streaming plasma.

Introduction

The CDAW substorm which occurs on 22 March 1979 provides an example of highly unusual plasma dynamics in the earth's magnetotail. The detailed sequence of events is described in the overview (McPherron and Manka, 1985). The essential points of relevance to this study are:

(i) A large isolated substorm occurs at 1054 UT. This is regarded as the main onset of the substorm.

(ii) At ~ 1057 UT the MPI instrument on ISEE 2 detects strong tailward streaming (Paschmann et al., 1985), simultaneous with a sharp rotation of the magnetic field in the southerly direction.

(iii) Between 1057 UT and 1116 UT intermittent net tailward streaming is observed on both ISEE spacecraft by plasma and energetic particle detectors.

(iv) After 1116 UT on ISEE 1 and after 1118 UT on ISEE 2 strong net earthward streaming is observed.

During the entire sequence of events both ISEE spacecraft are situated in the magnetotail close to local midnight and the neutral sheet, and are thus ideally placed to observe substorm effects. The data presented here are obtained by the Lepedea on board ISEE 1 and should be viewed as supplementary to the results of Paschmann et al. (1985). In the latter study emphasis is placed on the large velocities observed at ISEE 2 during the sequence of events. Here we focus on the details of the three-dimensional velocity distributions detected with the Lepedea, in particular the persistence of counterstreaming flows at low energies. This low-energy (~ 1-2 keV) component is clearly separated from the energetic (~ 20 keV) population which dominates the bulk velocity resulting from an integration over the entire velocity distribution.

Instrumentation

The University of Iowa Lepedea on ISEE 1 samples 32 passbands in the energy-per-unit charge range from 215 V to 45 kV in the high-energy mode. The energy levels are sampled sequentially, from lowest to highest, each level taking 16 seconds. At each energy level 16 azimuthal sectors are swept while 7 polar angles are simultaneously sampled in each azimuthal sector. A full three-dimensional distribution giving 3584 samples of velocity space is obtained in 8 minutes in this mode.

Energy-phase angle (E-ϕ) spectrograms provide details of the velocity distribution in terms of energy versus azimuthal angle for each of the seven fields of view of the instrument during each instrument cycle. Plates 1 and 2 show examples of such spectrograms. Responses are displayed for each of the seven ion and electron detectors and for the Geiger-Mueller tube. The detectors are numbered 1P through 7P for ions, where the center of the field-of-view of each detector ranges from 13° to the spacecraft spin axis (1P) through 90° (4P) to 167° (7P). A similar polar range is displayed for the electron sensors numbered 1E through 7E. The GM tube responds primarily to high-energy electrons ($E \gtrsim 45$ keV). The intensity maximum in the solar direction (panel center) is due to solar X-rays. Starting from the lowest energy level each detector sweeps through all azimuthal angles before the next energy level is sampled. The azimuthal angles plotted in each panel correspond to particles moving sunwards ($\phi = 0°$), duskwards ($\phi = 90°$), antisunwards ($\phi = 180°$), dawnwards ($\phi = 270°$) and again sunwards ($\phi = 360°$). For more details the reader is referred to Frank et al. (1978).

Observations

Details of the overall interplanetary conditions leading up to the substorm onset are given by McPherron and Manka (1984), who also describe the ground magnetic perturbations. Briefly, an interplanetary shock passes ISEE 3, located 230 R_E upstream from the earth, at 0742:23 UT causing increases in solar wind velocity, density and magnetic field strength. At 0923 UT a second discontinuity passes ISEE 3 producing a small increase in velocity with an additional increase in the magnetic field strength. This is accompanied by a sudden southward turning of the IMF. At IMP 8, located close to the earth's bow shock, this southward turning occurs at 1008 UT. The IMF remains southward for about 70 minutes. During this time the 55-station AE index exceeds 1000 nT.

A large expansion onset of the substorm occurs at 1054 UT. At 1057:30 UT rapid tailward flow, at speeds of ~ 650 km s^{-1}, is observed at ISEE 2 (Paschmann et al., 1985). This tailward streaming is accompanied by crossing of the neutral sheet, during which the magnetic field is strongly southward. B_z reaches a minimum of ~ -40 nT (GSM coordinates) in the seconds following the neutral sheet crossing. A detailed discussion of the magnetic variations is given by McPherron and Russell (1983). It is this coincidence of fast tailward streaming and negative B_z which makes this event so attractive from the point of the near-earth reconnection model of substorms. At ISEE 1 fast tailward streaming also occurs at 1057 UT, but the neutral sheet crossing is delayed until 1106:40 UT. The minimum B_z measured at ISEE 1 is ~ -12 nT, occurring at approximately 1110 UT. It has been pointed out by McPherron and Manka (1984) that there is a severe tilting of the entire tail, so that the neutral sheet position is approximately 10° south of its predicted position.

In order to see the full extent of the magnetic variations it is necessary to transform into this tilted coordinate system.

Figure 1 shows the plasma parameters for the 1000-1200 UT interval on 22 March 1979. The values are averaged over the eight-minute instrument cycle. The average density remains greater than 1 cm^{-3} until after 1112 UT, showing that the spacecraft does not encounter the lobe region during the first part of the interval. However brief excursions into the lobe would be obscured in our averaging process. The first instrument cycle for which we detect net tailward flow starts at 1054 UT. The value of V_x is only -10 km s^{-1}, and the ion velocity distribution consists of two separate components. These can be easily identified in Plate 1A which shows the instrument responses for this cycle. The bulk of the ion velocity distribution is centered at ~ 2 keV and exhibits an earthward-directed flow. AT 1057 UT a high-energy population is detected flowing tailwards, simultaneous with the tailward streaming observed on ISEE 2. The GM tube shows a brief increase in energetic electron fluxes during the same short period.

The same two-component velocity distribution can be seen in the following instrument cycle, which begins at 1103 UT. This is evident in Plate 1B, detectors 3P, 4P and 5P. The net value of V_x = -131 km s^{-1} but when the two components are separated, the low-energy portion centered at 2.6 keV has a value of V_x = 12 km s^{-1} and a density of 0.841 cm^{-3}. The high-energy component is flowing tailward at a speed of 456 km s^{-1} and has an integrated number density of 0.07 cm^{-3}. The energetic portion of the velocity distribution has a characteristic energy of 13.3 keV. The persistent presence of the low-energy population over two cycles strongly suggests that the low- and high-energy components are simultaneously present throughout and that the plasma velocity distribution comprises counterstreaming ions at different thermal energies. The overall similarity of the velocity distribution for the two instrument cycles can be seen in Figure 2 in which the peak count rate measured by detector 4P has been plotted for each 16-second spin as a function of azimuthal angle. This plot emphasizes the earthward and tailward flow directions, as this was a focus of the workshops. The individual instrument cycles are demarcated by dashed vertical lines. As noted in the previous section on instrumentation, the detectors sample energy passbands sequentially, starting with the lowest energy level and stepping up to successively higher energies every sixteen seconds. In Figure 2 low energies are plotted at the start of each cycle, and high energy at the end of the cycle. In addition the azimuthal angular sectors are 22.5° wide, and the peak count rates are plotted at the center of the sector's field of view. Note that in the cycle that begins at ~ 1046 UT the velocity distribution is quasi-isotropic, with relatively low count rates. During the next instrument cycle low-energy earthward flow is detected at the start of the cycle, while tailward flow is indicated at 1057-1058 UT. By 1103 UT the velocity distribution is distinctly bidirectional, the peak counting rates indicating low-energy ions flowing earthward and high-energy ions flowing tailward. Energetic earthward flow is observed for the first time at ~ 1116 UT.

The magnetic field components during the period are plotted in Figure 3 in GSM coordinates. The points represent 64-second averages. The neutral sheet crossing at ISEE 1 after the substorm expansion occurs at 1106:40 UT (McPherron and Manka, 1985) coincident with a southward turning of the magnetic field. As can be seen in Figure 3, bottom panel, the total magnetic field is at an absolute minimum of ~ 5 nT at this point. At this time the plasma detectors on ISEE 1 are sampling the low-energy range (see Plate 1B) and as shown in Figure 2, there is a large flux of ions convecting earthwards; i.e., the velocity perpendicular to the magnetic field, $V_{\perp}$ is large. The same convection direction is observed at ISEE 2 at this time (Paschmann et al., 1985). This neutral sheet crossing is markedly different from that on ISEE 2 in which the 1057:30 UT crossing coincides with the onset of strong tailward flow. The weak tailward flow observed at ISEE 1 at 1057 UT is not distinguished by any comparable magnetic signature. While the ISEE 2 observations, taken in isolation, are approximately compatible with near-earth reconnection occurring close to the spacecraft, the ISEE 1 results are not. The separation vector from ISEE 2 to ISEE 1 is $\vec{R}$ = (-9489, -796, 2318) km. If plasmoid formation occurs at ISEE 2 it must be of small scale size ($\lesssim 1.5\ R_E$) or highly distorted in order that the ISEE 1 instruments do not observe it. The implied scale size is inconsistent with ISEE 3 measurements in the distant magnetotail where the size of the plasmoid is approximately half the width of the plasma sheet (Slavin et al., 1985).

It has been argued by McPherron (1987) that just such a distortion occurs. The magnetotail during this event is deflected southward and extremely thin. The current sheet thickness is estimated to be ~ 500 km. A schematic diagram is shown by McPherron and Manka (1985). The positions of the two ISEE spacecraft are such that ISEE 2 is earthward of ISEE 1 and at lower latitudes. The interpretation presented by McPherron (1987) is that a neutral line forms earthward of ISEE 2, causing strong tailward flows at both spacecraft at 1057 UT. At this time ISEE 2 is located at the neutral sheet, where large negative B_Z is recorded. At approximately 1116 UT the neutral line moves tailward, and earthward-flowing plasma is observed at ISEE 1. At

1118 UT earthward flows are detected at ISEE 2. This time delay is ascribed to the distance between ISEE 2 and the neutral sheet, which is now closer to ISEE 1.

However the high-density, low-energy plasma flows directed earthward between 1054 UT and 1107 UT argue against this model. In addition, the net bulk flow measured at ISEE 2 is earthward between 1105-1107 UT. It should be noted that the counterstreaming ions detected between 1054 and 1107 UT at ISEE 1 are apparently coincident, i.e., the two populations occur simultaneously at the same location. In reconnection theory it is necessary to have a cross-tail electric field, $E_y > 0$, in order to accelerate plasma. It is difficult to reconcile this with the persistent earthward-flowing plasma at low energies. We rule out the possibility that the distant neutral line creates the low-energy plasma population by the following arguments.

(1) ISEE 3 studies of plasmoid formation indicate that even in the distant tail, flows are dominated by the near-earth neutral line. It is unlikely in the vicinity of the substorm reconnection line that effects due to the distant neutral line would be readily apparent.

(2) In order to produce flows which are simultaneously directed earthward directed and tailward, the electric field must reverse sign. It is unclear how this can occur at a single observation point to create counterstreaming $\vec{E} \times \vec{B}$ flows.

(3) As the plasmoid departs tailward soon after reconnection effects are detected at 1057 UT, the distant neutral line is effectively lost to the near-earth magnetosphere.

The onset of strong earthward flow at ISEE 1 before it is detected at ISEE 2 is a further problem in the neutral line model of this substorm. The explanation offered by McPherron (1987) and Paschmann et al. (1985) is based on the proximity (in the Z dimension) of ISEE 1 to the neutral sheet, relative to ISEE 2. As noted above ISEE 2 is approximately 1.5 R_E earthward, and 0.4 R_E southward of ISEE 1. In their model the neutral line moves tailward in such a way that ISEE 2 is outside of the fast flow region during the two-minute period of net earthward flow at ISEE 1. At 1118 UT ISEE 2 re-enters the reconnection region earthward of the neutral line and thus earthward flow is observed. However this implies that for at least two minutes ISEE 2 must lie in the lobe region outside of the earthward or tailward portions of the plasma sheet. This presumed excursion into the lobe is unmarked by a decrease in plasma pressure which would be expected (Paschmann et al., 1985). On the contrary it is at the onset of earthward flow at ISEE 2 that a plasma pressure decrease is recorded, similar to that seen at ISEE 1 (see Figure 1). This would be typical for an encounter with the plasma sheet boundary layer.

After 1120 UT the earthward-flowing ions persist but in addition a cold ionospheric component is also detected. The ionospheric ions are extensively discussed by Lennartsson et al. (1985) and Orsini et al. (1985). Responses to ionospheric ions can be seen in Plate 2A, for detectors 2P, 3P, 4P and 5P. The plasma density rises after the 1128 UT cycle as the plasma sheet begins to expand, but the recovering plasma sheet is characterized by a much higher thermal energy than that observed prior to substorm onset. This can be seen in the bottom panel of Figure 1. This is in agreement with the statistical study by Huang and Frank (1986) and that of Dandouras et al. (1986). The velocity distribution at this time shows an earthward-flowing ion beam embedded in a hot tenuous background (see Plate 2B). In detector 5P the ionospheric component can still be seen. At this time there is significant cross-field flow as the ionospheric ions are convecting towards dawn. The velocity components V_y and V_z are plotted in Figure 1. These components reach relative maxima at ~ 1130 UT. However it should be remembered that the velocities are computed for a population of H^+ only, while composition analysis (Orsini et al., 1985) shows a large percentage of O^+ which would reduce our estimated bulk speed.

The maximum bulk speed observed during the entire two-hour interval under study is recorded at ~ 1133 UT. This is due to the energetic earthward-directed ion beam which can be seen in Plate 2B. The speed at this time is 340 km s^{-1}, which is an average over the eight-minute cycle. This observation is made during the recovery phase of the substorm as the plasma sheet thickens. It is a common feature of the plasma sheet boundary layer that beams detected during the recovery phase of a substorm are systematically more energetic than those observed prior to a partial or total dropout (Eastman et al., 1985).

It should be noted that energetic earthward flows are observed from 1116 UT to 1137 UT, as opposed to approximately two minutes of strong tailward flow from 1057 to 1059 UT (see Paschmann et al., 1985). It is difficult to interpret the intensity and duration of these flows within the context of reconnection. Between 1059 UT and 1116 UT plasma bulk velocity is small ($|\vec{V}| < 100$ km s^{-1}) and directed tailward. If lobe field lines are being reconnected at this time, the plasma outflow suggests that most of the stored energy in the lobe magnetic field has already beeen dissipated at substorm onset. Yet the largest transfer of energy occurs with the start of earthward flow at 1116 UT, continuing for 21 minutes.

An interpretation in terms of a simple transition into the plasma sheet boundary layer, in which energetic earthward plasma flow is normal would seem less speculative. In this approach the source of the boundary layer plasma is situated at approximately 100 R_E (Williams, 1981), and may be the distant neutral line (Scholer et al., 1984). During the recovery, which is timed at 1142 UT (McPherron and Manka, 1985), the plasma sheet thickens so that ISEE 1 passes from the boundary layer back into the central plasma sheet. This can be seen in Figure 1. After 1137 UT flow speeds decrease to approximately 100-150 km s^{-1} and thermal energies are high.

Discussion

The main features of the substorm from the observations made at ISEE 1 can be summarized as follows:

(1) The first sign of tailward streaming occurs at ~ 1057 UT, nine minutes before the neutral sheet is crossed. Strong earthward flow occurs at ~ 1116-1137 UT.

(2) Low-energy ions with a characteristic energy of about 2 keV flow persistently earthward, even as high energy ions are flowing tailward. These low-energy ions constitute the bulk of the plasma population, although the energy density is carried by the energetic ions.

(3) Heavy ions from the ionosphere are observed during the main phase and recovery of the substorm.

(4) The earthward-directed beams detected at recovery are substantially more energetic and of longer duration than the tailward-flowing plasma associated with substorm onset.

(5) The plasma sheet upon recovery is characterized by a much higher thermal energy than that prior to onset.

If we consider the ISEE 1 observations alone, a possible interpretation would be that the plasma sheet thins at onset, so that the spacecraft samples the streaming plasma in the plasma sheet boundary layer. This would explain the increase in bulk speed, coincident with the decrease in density, shortly after 1111 UT. However energetic tailward streaming observed at 1057 UT at ISEE 2 and, to a lesser extent, at ISEE 1 suggests a localized acceleration region near both spacecraft. One postulated acceleration mechanism is near-earth reconnection (McPherron & Manka, 1985; Paschmann et al., 1985).

However a close examination of the details shows that this requires several assumptions concerning the spatial scale size of the neutral line which are inconsistent with measurements made in the distant magnetotail. It also leaves unexplained the persistence of the earthward-flowing plasma, or the intensity of the energetic earthward flows late in the substorm.

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Plate Captions

Plate 1A: This E-ϕ spectrogram shows the instrument responses at the time of substorm onset (1055 UT). The first sign of energetic particle streaming occurs at 1057 UT and is visible in all the ion detectors, labeled 1P through 7P. Note that a low-energy earthward-flowing ion velocity distribution is also present.

Plate 1B: This instrument cycle beginning at 1103 UT shows the persistence of the earthward-flowing population at 2 keV, simultaneous with tailward-flowing energetic ions.

Plate 1C: This cycle which continues from Plate 1A and 1B shows intense earthward-directed beams detected at high energies after 1116 UT. This is particularly clear in the responses of detectors 2P, 3P and 4P. The flow speeds during the recovery phase are considerably higher than the tailward flow observed at onset.

Plate 2A: This E-ϕ spectrogram displays the instrument responses for the cycle at 1120 UT. In addition to the energetic population which still shows a net earthward-directed velocity, multiple beams of cold ionospheric O^+ are clearly visible in the responses of detectors 2P through 5P.

Plate 2B: During this instrument cycle starting at 1128 UT the highest flow speed during the event is recorded. Earthward-flowing beams at the edge of the recovering plasma sheet are observed by detectors 3P and 4P. A response to ionospheric ions persists in detector 5P.

Plate 2C: In this plate is shown the instrument response for the cycle starting at 1137 UT. Relative to the spectrograms shown in Plates 1, 2A and 2B the velocity distribution is quasi-isotropic. The ionospheric ions seen here persist for several successive cycles.

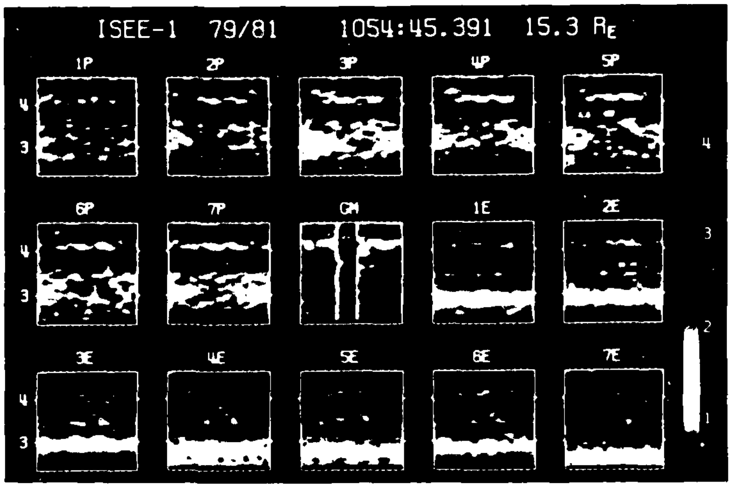
Figure Captions

Figure 1: In this figure are plotted the density, velocity and temperature of the plasma during the 1000-1200 UT interval on 22 March 1979. The values are eight-minute averages, the center of each bar corresponding to the midpoint of each plasma measurement. Error bars denote the standard deviation for each measurement. The velocity components are plotted in GSM coordinates.

Figure 2: The peak count rate measured by the 4P detector, which responds to ions in the ecliptic plane, is shown here as a function of azimuthal angle and time. The three symbols indicate the number of counts in a range from 10 to 70 counts/sec. The vertical dashed lines indicate the start of the instrument cycle. The detector responds to low energies (215 eV) at the beginning of each cycle, progressing successively to higher energies over the eight-minute cycle time. The low-energy (~ 2 keV) population persists throughout the substorm onset, in addition to the energetic component which exhibits first tailward, then earthward streaming.

Figure 3: The magnetic field components are plotted in GSM coordinates. Missing data are due to noise in the telemetry stream. These values are 64-second averages. The neutral sheet crossing occurs at 1106:40 UT, coincident with a southward turning of the magnetic field. However there is no tailward flow detected at ISEE 1 at this time.

A



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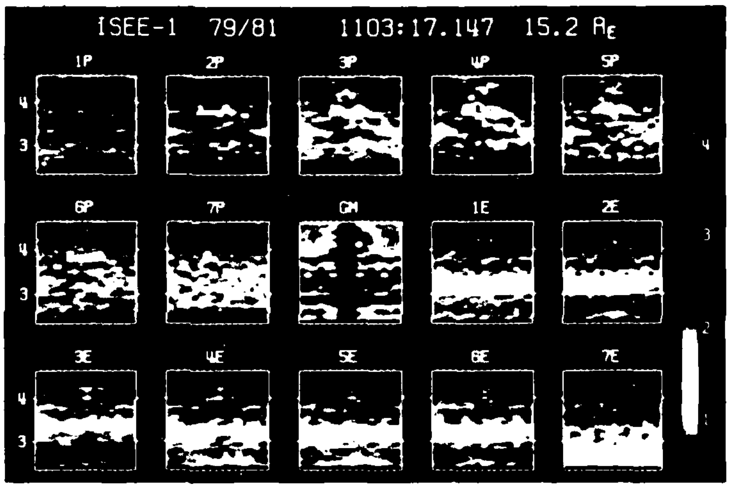

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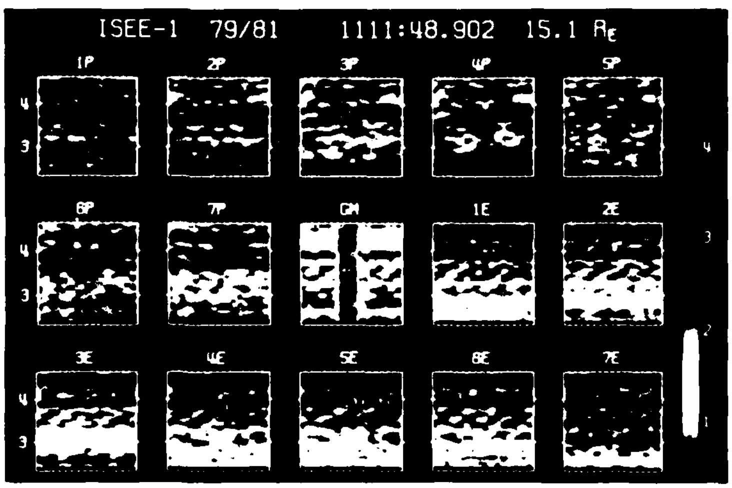

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Plate 1

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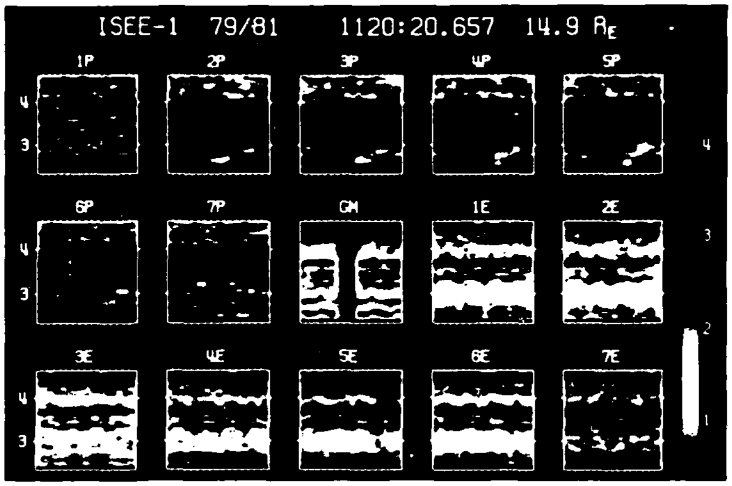
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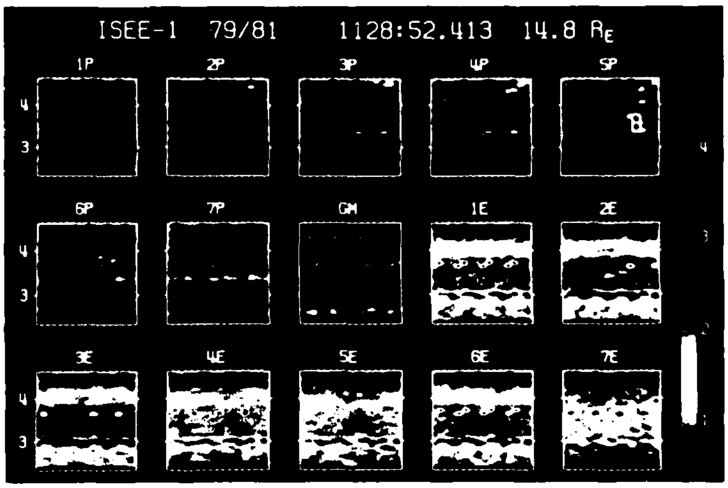
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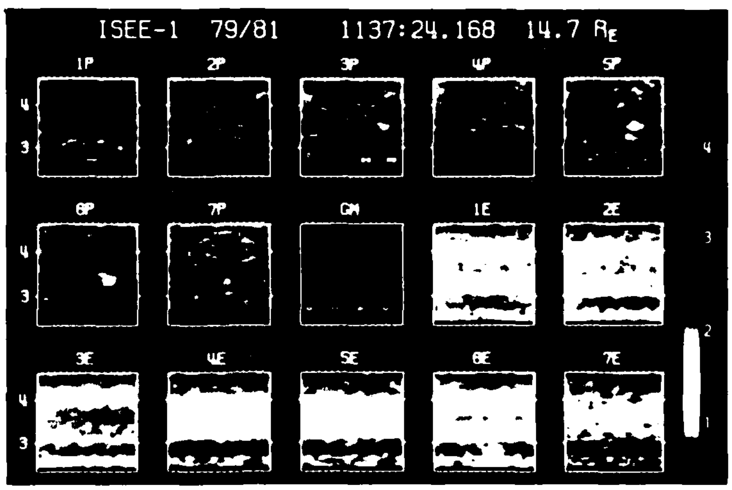
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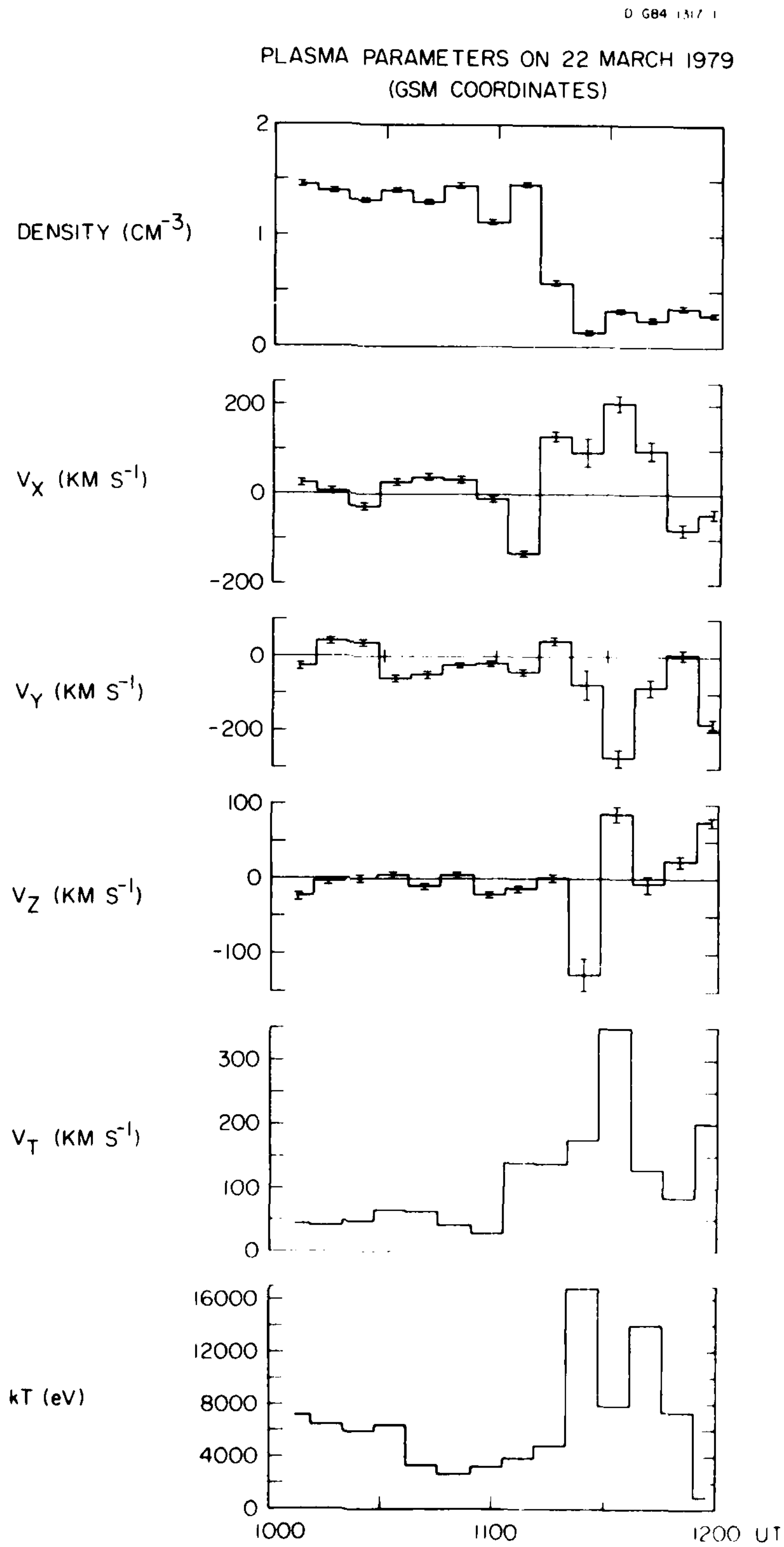
Plate 2



D G84 1317 1
PLASMA PARAMETERS ON 22 MARCH 1979
(GSM COORDINATES)
DENSITY (CM^-3)
2
1
0
V_X (KM S^-1)
200
0
-200
V_Y (KM S^-1)
0
-200
V_Z (KM S^-1)
100
0
-100
V_T (KM S^-1)
300
200
100
0
kT (eV)
16000
12000
8000
4000
0
1000
1100
1200 UT

Figure 1

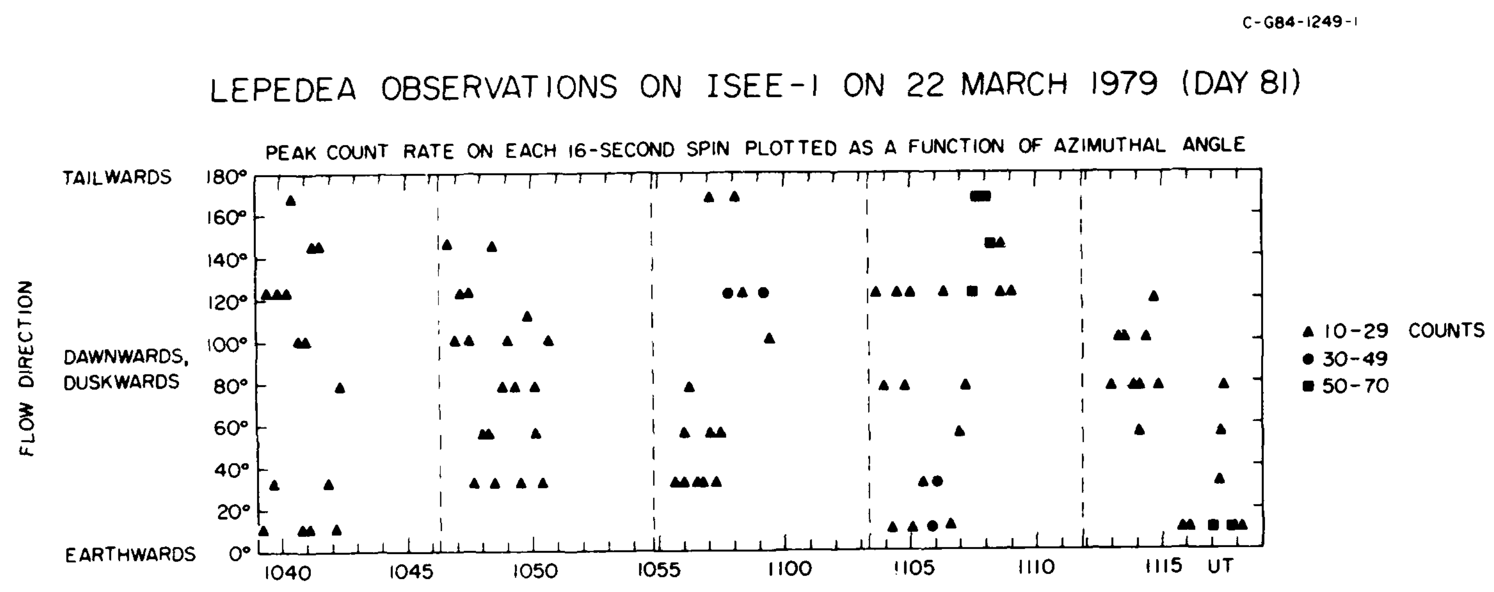

C-G84-1249-1
LEPEDEA OBSERVATIONS ON ISEE-1 ON 22 MARCH 1979 (DAY 81)
PEAK COUNT RATE ON EACH 16-SECOND SPIN PLOTTED AS A FUNCTION OF AZIMUTHAL ANGLE
FLOW DIRECTION
TAILWARDS
DAWNWARDS, DUSKWARDS
EARTHWARDS
180°
160°
140°
120°
100°
80°
60°
40°
20°
0°
1040
1045
1050
1055
1100
1105
1110
1115
UT
10-29 COUNTS
30-49
50-70

Figure 2

C-G84-1318

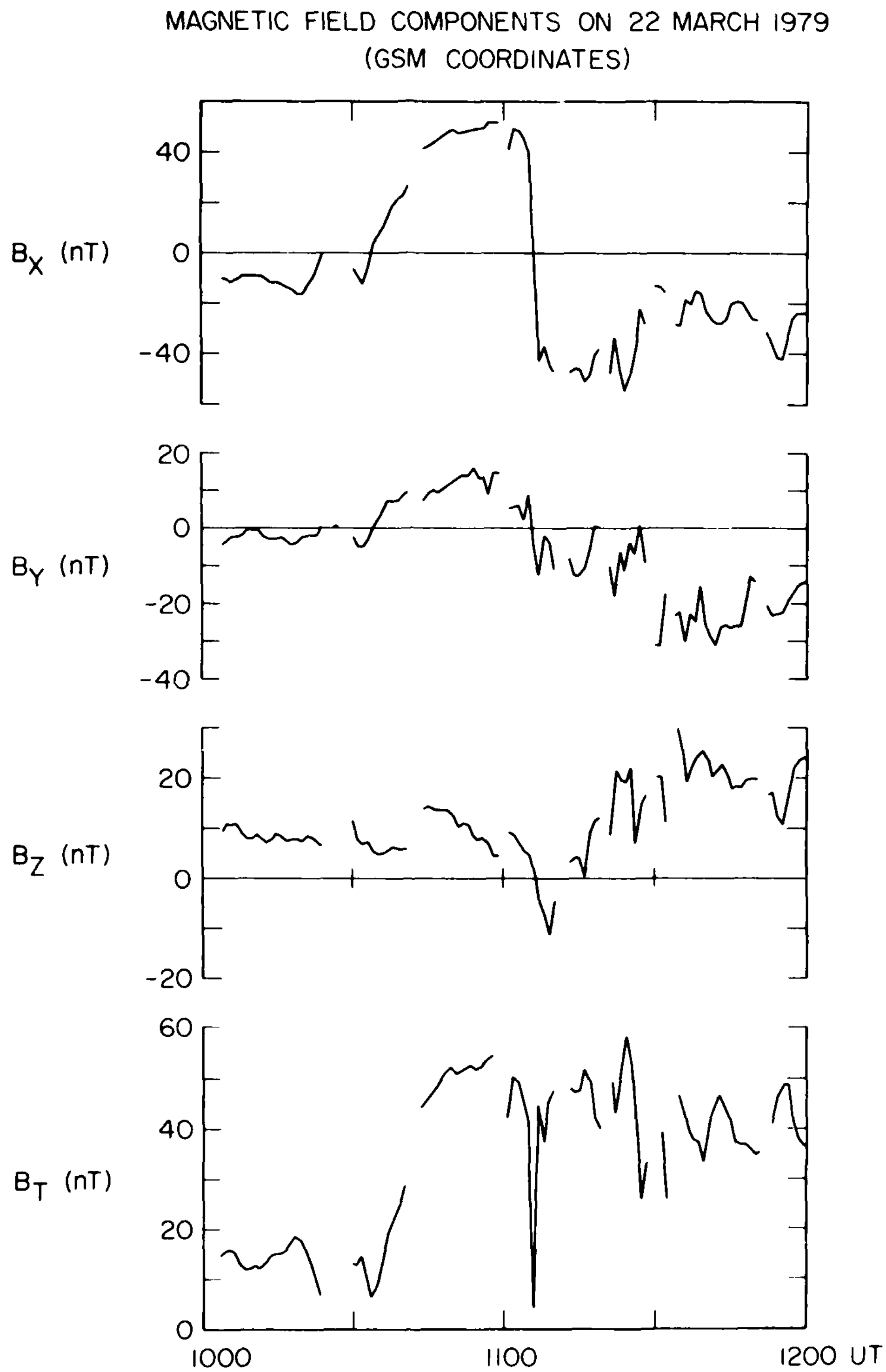


Figure 3

END
FILMED
MARCH, 1988
DTIC